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WO 98/16077 A2 US 5260968 A

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(54) Abstract Title
Base station transmission beam pattern forming; interference reduction

(57) A base station identifies, for a particular or desired mobile user, one or more other mobile users that are to be treated as vulnerable users potentially adversely affected by a downlink signal transmission from the base station to the desired user. A downlink transmission beam pattern is then formed which has a main beam with a direction matching the direction of the desired user and one or more nulls matching the direction or directions of one or more vulnerable users. Transmission data rate to the desired user and/or distance to the desired user may be used as criteria in determining whether this transmission is likely to render other users vulnerable to interference. A user data register (UDR) 14 stores data including direction of arrival (DOA) data for signals received by the base station from the desired and vulnerable users. From data in the UDR 14, a selection unit 16 determines one or more of: the DOA information for the desired user, distances of users from the base station, users who are close to high bit rate users, and users close to clusters of other users. From that data, a list of vulnerable users is generated by the unit 16 which sends the direction information for the desired and vulnerable users to an optimum weights unit 12 which calculates weights input to a downlink beamformer 20 so that the required beam pattern may be formed by transmission antenna elements. Any users for whom provision of a null would degrade the pattern for the desired user are removed from the vulnerable list. Where there is a cluster of vulnerable users, a null may be formed in the mean direction of the cluster. With N transmission antenna elements, N- 1 nulls can be formed, so that if there are more than N-1 vulnerable users, the N- 1 most vulnerable users are selected.

The receiving section of the base station may have an adaptive beamformer with an adaptive algorithm 26 which inputs a weight vector to a vector multiplier 22. A direction of arrival (DOA) determining unit 30 estimates the DOA of a user from the weight vector. The unit 30 may estimate the DOA by finding the peak of the uplink beam pattern, eg. by calculating the uplink beamformer gain at different DOAs and identifying the DOA for which the gain is the highest.

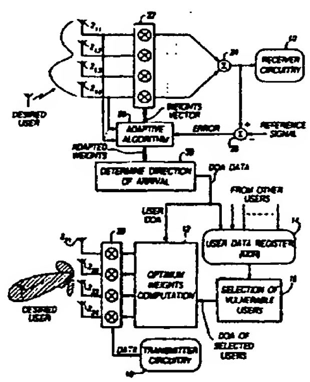

Fig.2

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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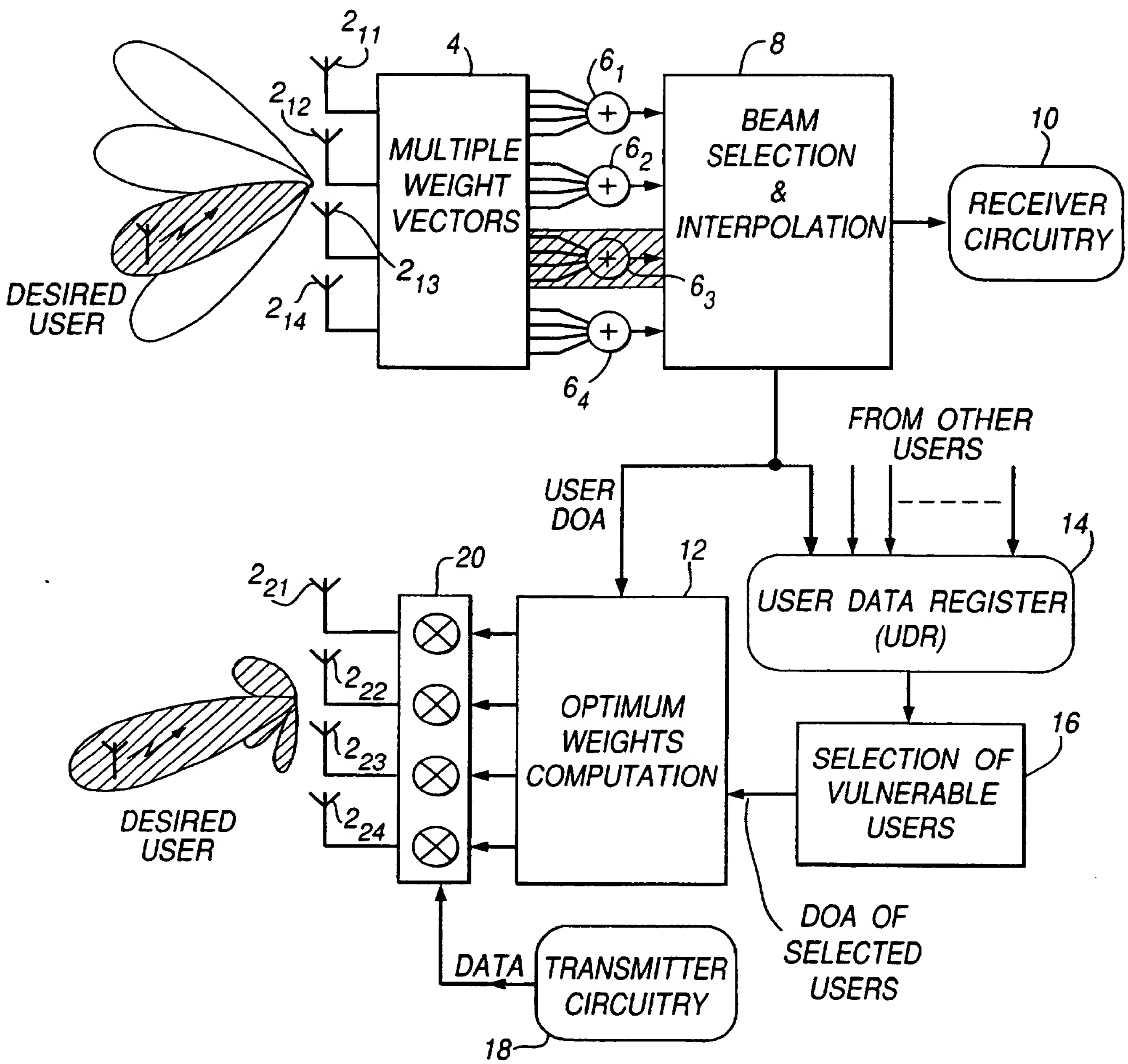
2_{11}
2_{12}
2_{13}
2_{14}
4
MULTIPLE WEIGHT VECTORS
6_1
6_2
6_3
6_4
8
BEAM SELECTION & INTERPOLATION
10
RECEIVER CIRCUITRY
DESIRED USER
FROM OTHER USERS
USER DOA
14
USER DATA REGISTER (UDR)
12
OPTIMUM WEIGHTS COMPUTATION
20
2_{21}
2_{22}
2_{23}
2_{24}
DESIRED USER
16
SELECTION OF VULNERABLE USERS
DOA OF SELECTED USERS
DATA
TRANSMITTER CIRCUITRY
18

Fig.1

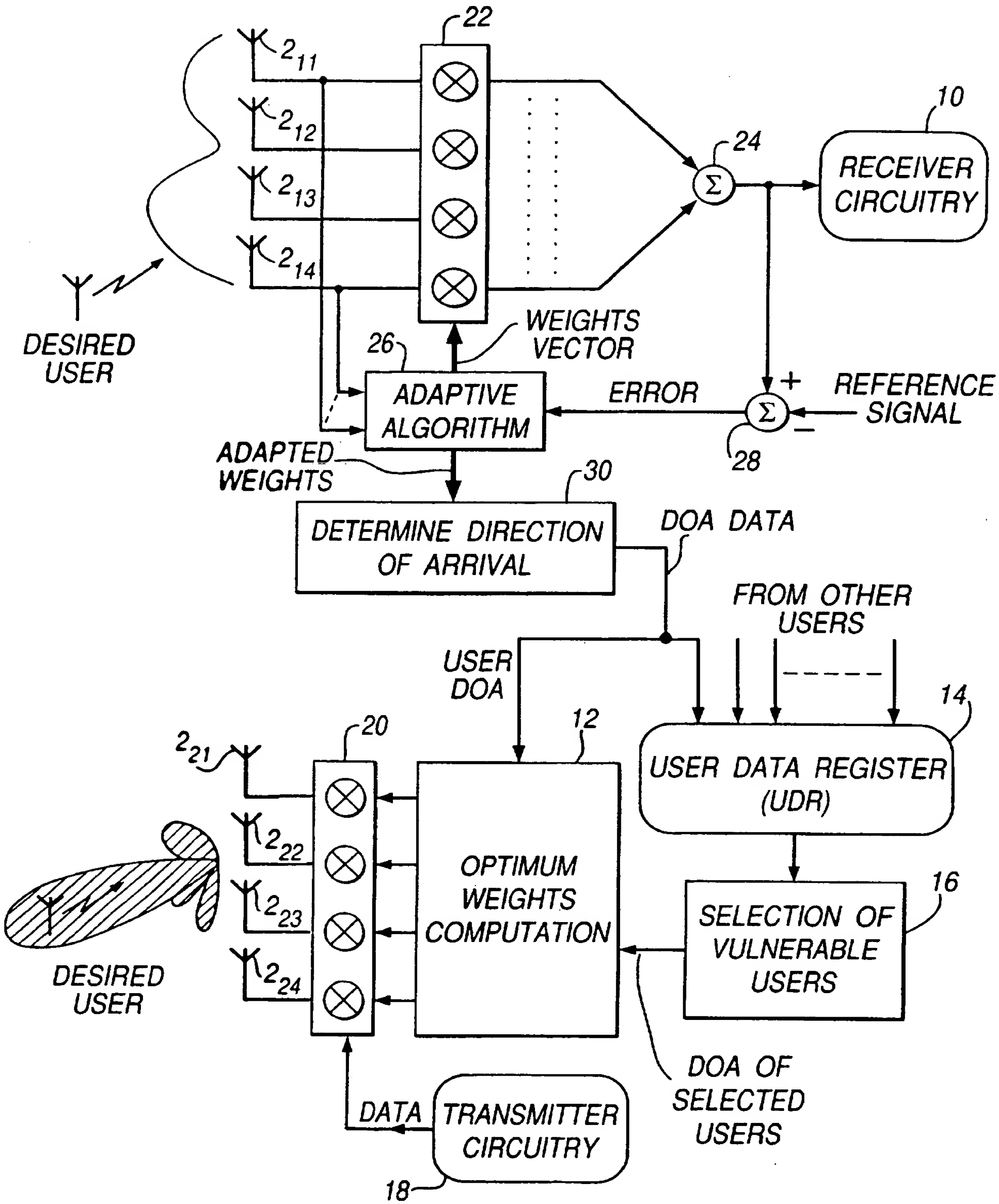
22
2_{11}
2_{12}
2_{13}
2_{14}
10
24
RECEIVER CIRCUITRY
DESIRED USER
26
WEIGHTS VECTOR
ADAPTIVE ALGORITHM
ERROR
+
REFERENCE SIGNAL
−
28
ADAPTED WEIGHTS
30
DETERMINE DIRECTION OF ARRIVAL
DOA DATA
FROM OTHER USERS
USER DOA
14
12
20
2_{21}
USER DATA REGISTER (UDR)
2_{22}
2_{23}
2_{24}
OPTIMUM WEIGHTS COMPUTATION
16
SELECTION OF VULNERABLE USERS
DESIRED USER
DOA OF SELECTED USERS
DATA
TRANSMITTER CIRCUITRY
18

Fig.2

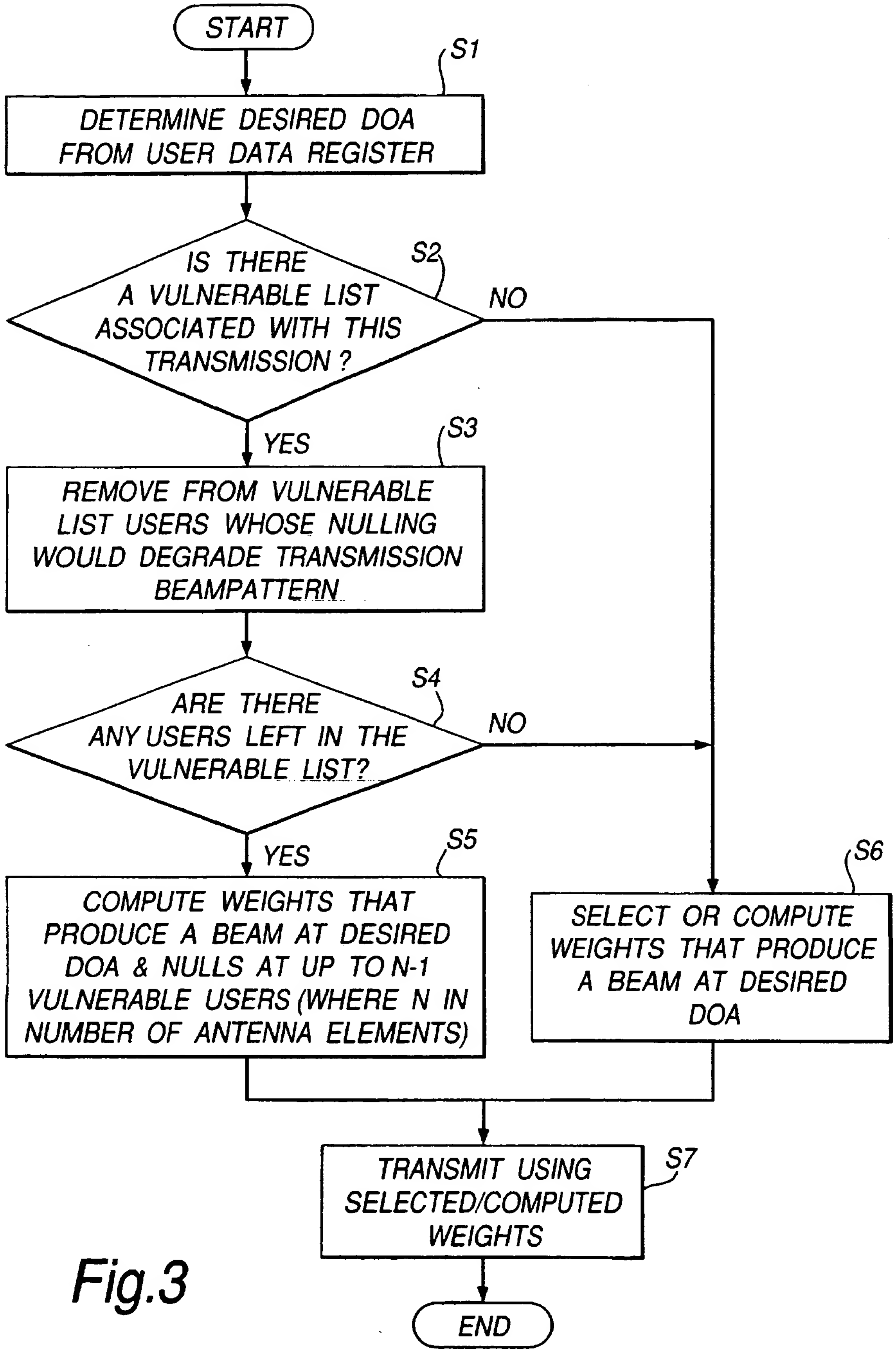
START
S1
DETERMINE DESIRED DOA FROM USER DATA REGISTER
S2
IS THERE A VULNERABLE LIST ASSOCIATED WITH THIS TRANSMISSION ?
NO
YES
S3
REMOVE FROM VULNERABLE LIST USERS WHOSE NULLING WOULD DEGRADE TRANSMISSION BEAMPATTERN
S4
ARE THERE ANY USERS LEFT IN THE VULNERABLE LIST?
NO
YES
S5
COMPUTE WEIGHTS THAT PRODUCE A BEAM AT DESIRED DOA & NULLS AT UP TO N-1 VULNERABLE USERS (WHERE N IN NUMBER OF ANTENNA ELEMENTS)
S6
SELECT OR COMPUTE WEIGHTS THAT PRODUCE A BEAM AT DESIRED DOA
S7
TRANSMIT USING SELECTED/COMPUTED WEIGHTS
END

Fig.3

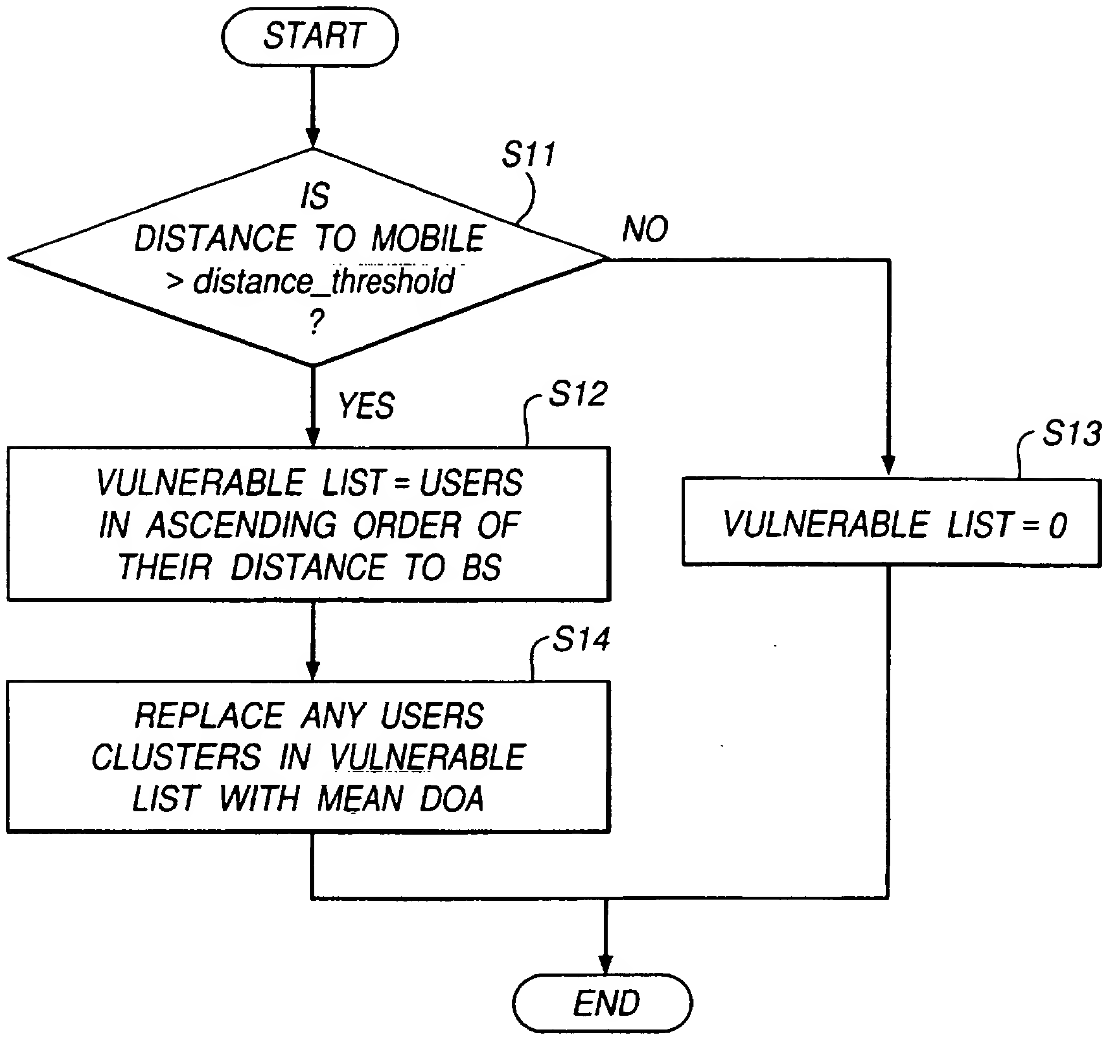
START
IS
DISTANCE TO MOBILE
> distance_threshold
?
S11
NO
YES
S12
VULNERABLE LIST = USERS
IN ASCENDING ORDER OF
THEIR DISTANCE TO BS
S13
VULNERABLE LIST = 0
S14
REPLACE ANY USERS
CLUSTERS IN VULNERABLE
LIST WITH MEAN DOA
END

Fig.4

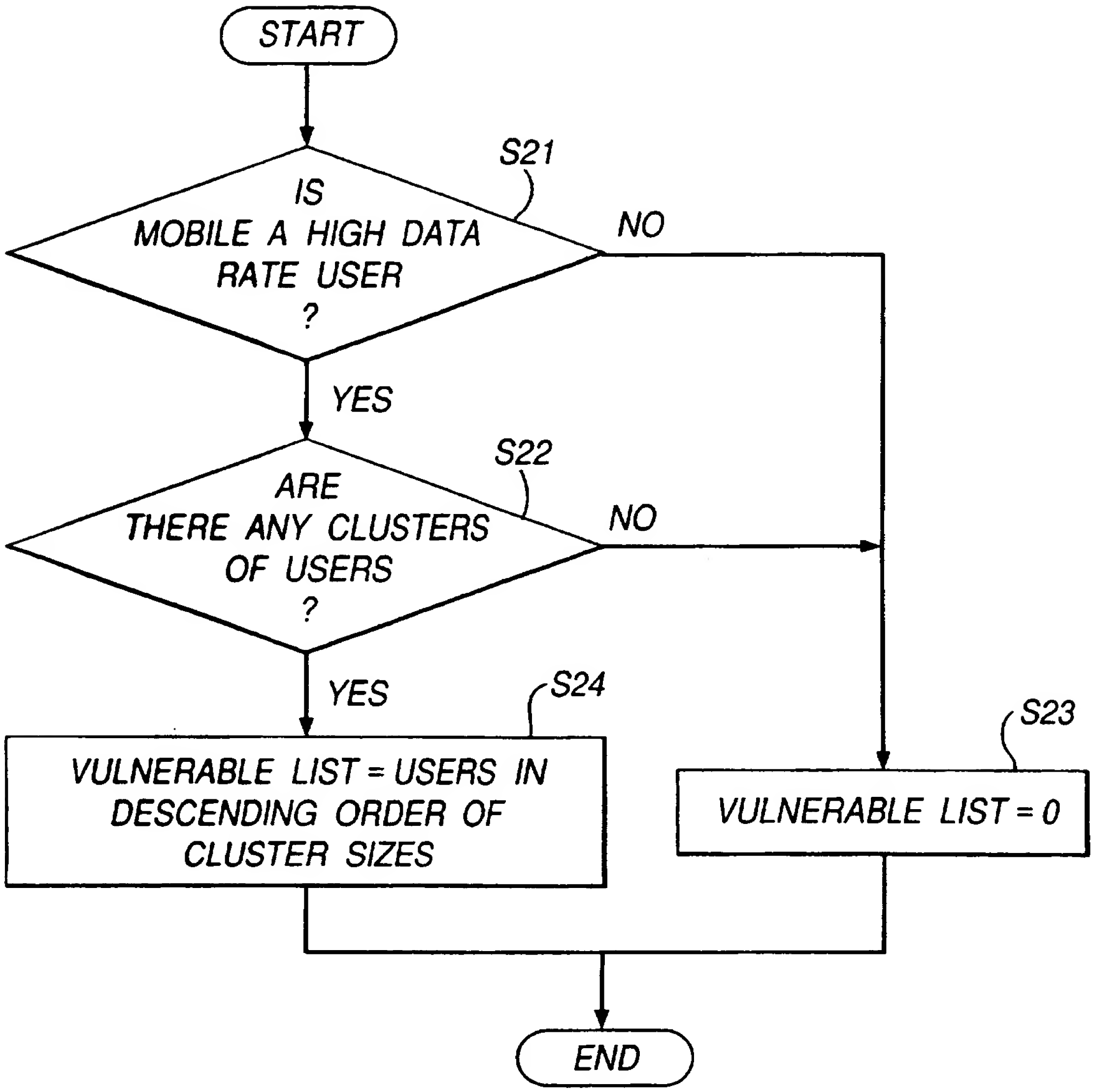
START
IS MOBILE A HIGH DATA RATE USER ?
S21
NO
YES
ARE THERE ANY CLUSTERS OF USERS ?
S22
NO
YES
S24
VULNERABLE LIST = USERS IN DESCENDING ORDER OF CLUSTER SIZES
S23
VULNERABLE LIST = 0
END

Fig.5

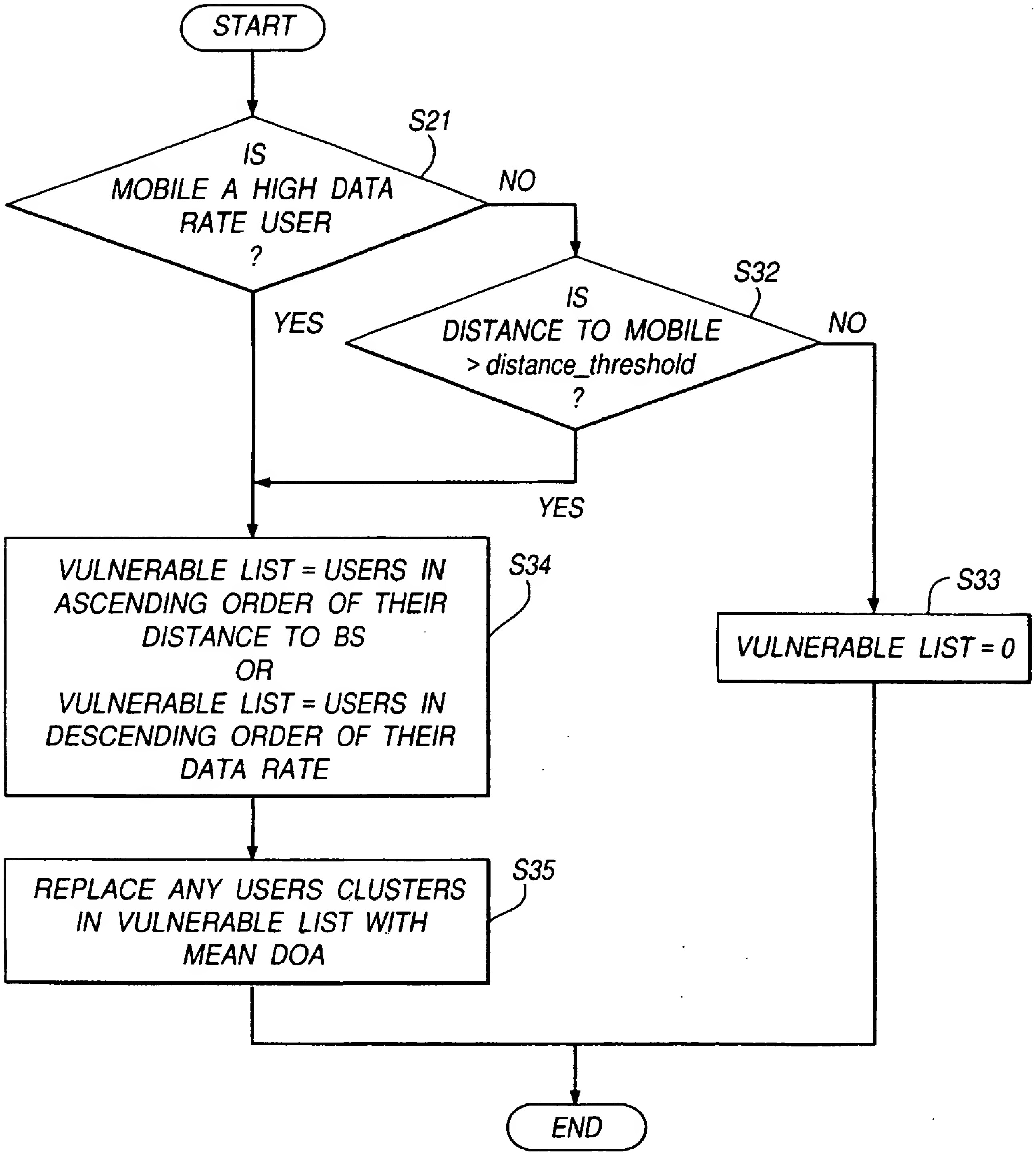
START
IS MOBILE A HIGH DATA RATE USER ?
S21
NO
YES
IS DISTANCE TO MOBILE > distance_threshold ?
S32
NO
YES
VULNERABLE LIST = USERS IN ASCENDING ORDER OF THEIR DISTANCE TO BS
OR
VULNERABLE LIST = USERS IN DESCENDING ORDER OF THEIR DATA RATE
S34
S33
VULNERABLE LIST = 0
REPLACE ANY USERS CLUSTERS IN VULNERABLE LIST WITH MEAN DOA
S35
END

Fig.6

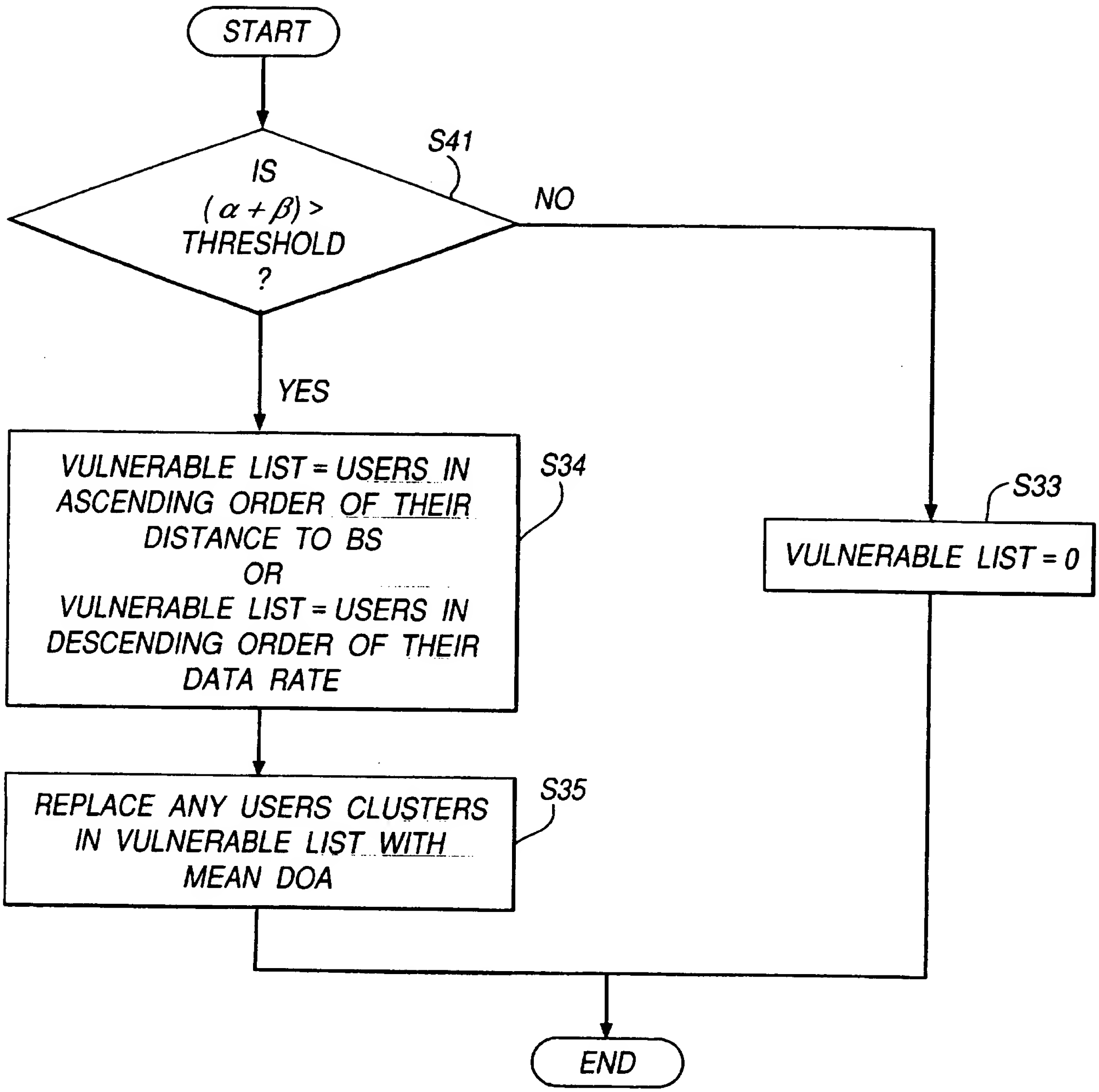
START
IS
$(\alpha + \beta) >$
THRESHOLD
?
S41
NO
YES
VULNERABLE LIST = USERS IN ASCENDING ORDER OF THEIR DISTANCE TO BS
OR
VULNERABLE LIST = USERS IN DESCENDING ORDER OF THEIR DATA RATE
S34
S33
VULNERABLE LIST = 0
REPLACE ANY USERS CLUSTERS IN VULNERABLE LIST WITH MEAN DOA
S35
END

Fig.7

TRANSMISSION METHODS AND APPARATUS

The present invention relates to transmission methods and apparatus. In particular, but not exclusively, the present invention relates to transmission methods and apparatus for use in a base station of a cellular mobile communications system.

In a cellular mobile communications system, it is necessary for a base station to be able to detect uplink signals transmitted by a desired mobile station (user) to the base station and be able to transmit downlink signals back to that desired user.

A given desired user may be at any angular direction from the base station and a simple approach to transmission and detection of signals would be to transmit and "look for" all signals in all directions.

However, adaptive antennae techniques and beamforming techniques have been proposed for use in mobile communications systems such as the Universal Mobile Telecommunication System (UMTS). These techniques can provide improvements in performance and/or spectral efficiency of the system.

Most of the proposed adaptive antennae/beamforming techniques have been applied to reception of uplink signals at the base station. The principle underlying one such uplink beamforming technique is to process signals received from an adaptive antenna array at the base station to form a spatial beam pattern such that the angle of arrival of the uplink signal of a wanted user falls well within a main lobe of the beam pattern whereas interfering signals from other users are located as much as possible in the nulls, low side lobes or boundary regions of the main lobe.

However, as such uplink beamforming techniques improve, transmission of downlink signals from the base

station is becoming the system bottleneck. Downlink beamforming is one approach being considered to alleviate this potential bottleneck.

In Time Division Duplexing (TDD) systems, the channel between the desired user and the base station can be assumed to be the same for the uplink and the downlink. Therefore, if uplink beamforming is being performed, exactly the same beam pattern can be used for the downlink as in the uplink.

In Frequency Division Duplexing (FDD) systems the channel estimation performed in the uplink cannot be directly applied to the downlink. Due to the difference in frequency, there is no channel-impulse-response reciprocity between the uplink and the downlink. Beam reciprocity, however, does exist provided that the channel is substantially static between reception and transmission. Downlink beamforming can then be applied by simply pointing a beam in the user direction during transmission.

However, although such downlink beamforming approaches are expected to result in better performance than omnidirectional transmission, these approaches do not take into account the possible adverse affects on other users of the downlink signal transmission to a particular wanted user.

According to a first aspect of the present invention, there is provided a transmission method, for use in a mobile communications network, including the steps of: in a base station of the network, identifying, for a particular user of the network, one or more other mobile users that are to be treated as vulnerable users potentially adversely affected by a downlink signal transmission from the base station to the particular mobile user; determining a downlink beam pattern including a main beam having a direction matching a direction of the particular mobile user and

also including a null having a direction matching a direction of at least one of the said vulnerable users; and transmitting such a downlink signal to the said particular mobile user using the determined beam pattern.

Such a transmission method can form a more intelligent transmission beam pattern comprising a pointed beam and some nulls, the nulls being selected using user information available to the base station.

Incidentally, the term "matching", as used herein, does not require absolute equality of direction; only approximate equality is intended and some angular divergence is contemplated in practical systems.

In one embodiment the direction of the said particular mobile user and of the or each said vulnerable user is determined by processing an uplink signal received at the base station from the user concerned. Such a transmission method has the advantage that it makes use of information readily available in the base station.

Preferably, the said direction of the said particular mobile user and of the or each said vulnerable user is derived from an uplink beam pattern employed by the base station to process a received uplink signal from the user concerned. Such a transmission method has the advantage that it makes use of information readily available in the base station.

In one embodiment, the uplink beam pattern is adapted in use by the said base station; and an estimate of the direction of each said mobile user is derived from an adjustable weight vector corresponding to the uplink beam pattern determined for that user. Such a transmission method has the advantage that it makes use of information readily available in the base station.

Preferably, in the pattern determining step, any

identified vulnerable user whose direction would require the said downlink beam pattern to include such a null within, or near to, the said main beam is ignored. Such a transmission method has the advantage that the quality of the transmission to the desired user is not greatly degraded.

In one embodiment, the said downlink beam pattern is calculated based on the respective directions of the said particular mobile user and the or each said vulnerable user. Such a transmission method has the advantage that the locations of the peak and the nulls of the beam can be optimised.

Alternatively, in another embodiment, the determined downlink beam pattern is a best-matching downlink beam pattern selected from amongst a plurality of predetermined candidate downlink beam patterns. Such a transmission method has the advantage that the complexity of mathematical calculation required for each downlink signal to be transmitted is reduced.

One embodiment further includes an interference judging step of judging, for the said particular mobile user, whether, based on one or more predetermined criteria, the said downlink signal transmission to that user is likely to cause significant interference to other mobile users of the network and, if not, of omitting the said step of identifying vulnerable users and of determining the said downlink beam pattern for the particular mobile user independently of the effect of that transmission on other mobile users of the network. Such a transmission method has the advantage that complex calculation is avoided when it is not needed.

In this embodiment, preferably, the said one or more predetermined criteria used in the interference judging step relate exclusively to the particular mobile user. In this way, it can be determined

desirably simply whether or not it will be worthwhile identify vulnerable users.

The predetermined criteria used in the interference judging step may, for example, include one or more of the following:

a measure of the distance of the said particular mobile user from the base station; and a bit rate of the said downlink signal transmission to the said particular mobile user. Such information is readily available in the base station.

In one embodiment, in the said interference judging step it is judged that significant interference to other users is likely when a measure of the distance of the said particular mobile user from the base station exceeds a predetermined threshold value. This basis for judging interference is desirably simple but is effective because when the particular mobile user under consideration is relatively far from the base station the downlink transmission power to that user tends to be high, giving rise to significant interference to other users.

Alternatively, or in addition, in the interference judging step it may be judged that significant interference to other users is likely when a bit rate of the said particular mobile user exceeds a predetermined threshold value. This basis for judging interference is again simple but highly effective.

In one embodiment, in the step of identifying vulnerable users it is determined whether a mobile user other than the said particular mobile user is to be treated as a vulnerable user in dependence upon one or more of the following criteria:

the direction of that other mobile user; a measure of the distance of that other mobile user from the base station; a bit rate of that other mobile user; and a proximity of that other mobile user to further mobile

users of the network. Such a transmission method has the advantage of making use of information readily available in the base station.

Preferably, candidate mobile users other than the said particular mobile user are ranked in order of vulnerability according to the said criteria used in the identifying vulnerable users step and, when the number of other users exceeds the number N_{max} of nulls/low side lobes that it is possible to form in the said downlink beam pattern, the N_{max} most vulnerable candidate users in the said order are selected as vulnerable users for determining the downlink beam pattern. Such a ranking process is advantageous in environments where there are large numbers of mobile users, and permits identification of the most vulnerable users in a systematic manner.

In one embodiment, in the identifying vulnerable users step it is determined whether there are any clusters of other users and, if so, the clusters are ranked according to the numbers of users therein. Again, when there are large numbers of users in various clusters, this step enables the most vulnerable users to be prioritised so as to achieve the best overall result in terms of interference reduction.

In one embodiment, vulnerable users that form a cluster are processed collectively as a vulnerable cluster and the downlink beam pattern determined for the said particular mobile user is such as to include such a null having a direction matching a direction of the said vulnerable cluster. Such a collective processing method can enable the number of users for whom potential interference is reduced to be maximised, even when the total number of users exceeds the maximum number of possible nulls that can be formed.

The direction of the said vulnerable cluster may be determined based on an average of the respective

directions of the individual vulnerable users making up the cluster concerned. This average is easily calculable.

In one embodiment, the said distance measure for a mobile user is, or is derived from, a transmission power determined by the base station for transmitting a downlink signal to the user concerned. Such a transmission method has the advantage that it makes use of information already available in the base station in many networks.

Alternatively, the said distance measure for a mobile user may be, or may be derived from, a code time offset of an uplink signal received by the base station from the mobile user concerned. Such a transmission method has the advantage that it makes use of information already available in the base station in some networks.

Alternatively, the said distance measure for a mobile user and/or the said direction of a mobile user may be derived from information obtained using a satellite-based global positioning system (GPS). Such a transmission method has the advantage that the distance measures derived can be calculated with a great degree of accuracy. Some networks already use such a GPS based location system for emergency purposes.

Alternatively, in another embodiment, the said distance measure for a mobile user and/or the direction of a mobile user is derived from information obtained using triangulation techniques involving at least three base stations of the said network. Such a transmission method has the advantage that the distance measures derived can be calculated with a great degree of accuracy.

According to a second aspect of the present invention there is provided transmission apparatus, for

use in a base station of a mobile communications network, comprising: identification means operable to identify, for a particular mobile user of the network, one or more other mobile users that are to be treated as vulnerable users potentially adversely affected by a downlink signal transmission from the base station to the particular mobile user; determining means operable to determine a downlink beam pattern including a main beam having a direction matching a direction of the particular mobile user and also including a null having a direction matching a direction of at least one of the said vulnerable users; and transmission means operable to transmit such a downlink signal to the said particular mobile user using the determined beam pattern.

Such a transmission apparatus can form a more intelligent transmission beam pattern comprising a peak and some nulls, the peak and the nulls being selected using user information available to the base station.

In one embodiment, the apparatus further includes user data register means operable to store, for each of a plurality of mobile users of the said network, one or more predetermined items of information about the user concerned for use by the identification means to identify vulnerable users and/or by the determining means to determine the downlink beam pattern.

Such an apparatus has the advantage that required information about mobile users is stored in a readily accessible means.

In this embodiment, preferably, the stored items of information about each user include one or more of the following types of information: the direction of the mobile user; a measure of the distance of the mobile user from the base station; a bit rate of the mobile user; a position of the mobile user; and cluster information as to proximity of the mobile user to other

mobile users of the network. Such types of information about users are easily obtainable in the base station.

According to a third aspect of the present invention there is provided a base station for use in a mobile communications network, which includes transmission apparatus embodying the aforesaid second aspect of the present invention.

Such a base station can form a more intelligent transmission beam pattern comprising a peak and some nulls, the peak and the nulls being selected using user information available to the base station.

According to a fourth aspect of the present invention there is provided an angle-of-arrival calculation method, for use in receiving apparatus that includes an antenna array having a plurality of antenna elements for sampling, at different respective locations in space, a wanted signal transmitted to the apparatus and that also includes an adaptive beamformer operable to process a set of receive signals, derived respectively from the antenna elements of the array, in accordance with a beam pattern determined by an adjustable weight vector, the weight vector being adjusted in use of the apparatus in response to changes in an angle-of-arrival of the wanted signal at the antenna array, which method includes the steps of: processing the said adjustable weight vector to determine an angle-of-arrival of the wanted signal at which the response of the adaptive beamformer has a peak; and outputting a measure of angle-of-arrival of the said wanted signal based on the determined angle of peak beamformer response.

Such an angle-of-arrival calculation method can estimate the angle of arrival of an uplink signal from the uplink beam pattern without complex calculation.

Preferably, the said processing step comprises: determining the uplink beam pattern corresponding to

the current value of the said adjustable weight vector; calculating the uplink beamformer gain at a plurality of different possible angles-of-arrival according to the said uplink beam pattern; and selecting the angle-of-arrival for which the uplink beamformer gain is the greatest.

Such an angle-of-arrival calculation method can estimate the angle of arrival of an uplink signal from the uplink beam pattern without complex calculation.

Reference will now be made, by way of example, to the accompanying drawings, in which:

Figure 1 is a block diagram of parts of a base station including transmission apparatus according to a first embodiment of the present invention;

Figure 2 is a block diagram of parts of a base station including transmission apparatus according to a second embodiment of the present invention;

Figure 3 is a flowchart illustrating an example of a transmission method for use in the apparatus of Figures 1 and 2;

Figure 4 is a flowchart of a process which may be used in a part of the apparatus of Figures 1 and 2;

Figure 5 is a flowchart of a second process which may be used in a part of the apparatus of Figures 1 and 2;

Figure 6 is a flowchart of a third process which may be used in a part of the apparatus of Figures 1 and 2; and

Figure 7 is a flowchart of a fourth process which may be used in a part of the apparatus of Figures 1 and 2.

A transmission method embodying the present invention seeks to optimise the transmission pattern for a particular mobile station by taking into account information on the other mobile stations within the

system. In addition to forming a narrow beam in the direction of the desired user, nulls may also be placed in the direction of one or more other "vulnerable" users, i.e. users who are likely to be adversely affected by the downlink signal transmission to that desired user. The effect of this should be to reduce interference levels at these mobile units and hence improve the system's performance and capacity.

In systems having very few active users it may be possible to take into account all other users when setting the downlink beam pattern for a particular user. However, in most practical systems the number of active users will far exceed the number of users for which nulls can be formed, so in a preferred embodiment of the present invention, certain criteria are used to determine which mobile units are the most vulnerable to interference, and hence should have nulls in their directions during downlink transmission.

Alternatively, or in addition, certain criteria are used to determine whether the transmission to a given mobile unit is likely to cause interference and hence whether users vulnerable to interference need to be determined.

For example, generally speaking, when a base station transmits a downlink signal to a mobile station far away from the base station it transmits using a higher power level than for a mobile station close to the base station. Therefore a transmission from the base station to a far-away mobile station will cause more interference than a transmission to a nearby one. Also, a nearby mobile station, to which the base station is transmitting its downlink signal at a relatively low power, will be particularly adversely affected by a high-power transmission from the base station to a far-away mobile station since the nearby mobile station experiences a low signal-to-

interference-and-noise ratio (SINR).

High-bit-rate (data rate) users are also more likely to cause and be affected by interference than low-bit-rate users. Therefore, in some types of system, for example a system with small cells that typically serve a large number of high-bit-rate users, bit rate could be used to select vulnerable users.

As an example, some of the following types of information about users might be used to determine vulnerable users: knowledge of the direction of arrival of signals from all users, knowledge of the relative distance of the users from the base station, knowledge of high-bit-rate users and knowledge of clusters of users.

In a base station in which beamforming is performed on the uplink, information about direction of arrival (DOA) of uplink signals from all the users within a given cell should be known to the base station.

Knowledge of the relative distance of users from the base station can be obtained using a number of methods. In one method, the relative distance from the base station of a given mobile unit can be estimated from a downlink transmission power determined for the mobile unit by the transmission power control (TPC) circuitry in the base station; the lower the transmitted power (TPC setting), the closer the mobile unit is assumed to be to the base station. As an alternative, code time offsets could be used to estimate the relative distances of the users from the base station.

Alternatively, a position location system may be used by the mobile communications system to obtain DOA and/or distance information for the users in the cell. This may involve a satellite-based global positioning system (GPS) or terrestrial triangulation techniques.

For example, if the uplink signal from a mobile station is received by three base stations, then its exact location, and therefore DOA and distance from any of the base stations, can be calculated.

Data identifying high-bit-rate users is readily available at the base station and information about clusters of users is easily determined from DOA information available at the base station.

It will be appreciated that in many systems the number of available nulls in the transmission beam pattern will be insufficient to permit nulls to cover the vulnerable users individually, but in this situation providing a null corresponding to a cluster of users can still enable the overall system performance and capacity to be improved.

It should be noted that embodiments of the present invention are not restricted to the use of any one uplink beamforming technique.

Transmission apparatus according to a first embodiment of the present invention is illustrated in Figure 1, together with receiving apparatus capable of performing multibeam uplink beamforming.

The receiving apparatus comprises a first array of antenna elements 2_{11} to 2_{14} connected via respective down-converters (not shown) to a multiple vector multiplier unit 4. The multiple vector multiplier unit 4 comprises M sets of complex-conjugate multipliers, where M (= 4 in this embodiment) is the number of different trial (uplink) beam patterns formed by the receiving apparatus. Each of the M sets of multipliers has N multipliers, where N (= 4 in this embodiment) is the number of antenna elements in the first array. Each of the M sets of multipliers has a corresponding uplink weight vector associated with it for defining the trial beam pattern with which it is to process the receive signals produced by the antenna elements 2_{11} to

2_{14}. It should be noted that the values of N and M do not have to be 4 and can be different from each other.

The multiple vector multiplier unit 4 is in turn connected, via a set of combiners 6_1 to 6_4, to a beam selector 8.

The receiving apparatus also comprises receiver circuitry 10 connected to an output of the beam selector 8.

The transmission apparatus comprises a user data register (UDR) 14, an optimum weights computation unit 12 and a vulnerable users selection unit 16.

The UDR 14 has a plurality of data inputs connected to other parts of the base station for receiving therefrom data signals corresponding to each user. These data signals include a user DOA signal corresponding to each user produced by the beam selector 8 in the receiving apparatus. The user DOA signal for the desired user is also passed to the optimum weights computation unit 12. The vulnerable users selection unit 16 has an input connected to the UDR 14 and an output connected to the optimum weights computation unit 12.

The Figure 1 apparatus further comprises transmitter circuitry 18, a downlink beamformer 20 and a second array of antenna elements 2_{21} to 2_{24}. The downlink beamformer 20 comprises P complex-conjugate multipliers, where P (= 4 in this embodiment) is the number of antenna elements in the second array. P need not be the same as N, although this may be preferable for simplifying the processing required.

Each multiplier in the downlink beamformer 20 is connected to receive one of a set of P weight values, making up a weight vector, from the optimum weights computation unit 12 and is also connected to receive from the transmitter circuitry 18 data to be transmitted to the desired user. Each multiplier in

the downlink beamformer 20 produces a transmit signal, which is applied to a corresponding one of the antenna elements 2_{21} to 2_{24} of the second array.

Operation of the Figure 1 apparatus will now be described. In use, the multiple vector multiplier unit 4, the set of combiners 6_1 to 6_4 and the beam selector 8 together serve as a multibeam uplink beamformer. To receive an uplink signal from a particular desired user each set of multipliers in the multiple weight vectors unit multiplies the receive signals, produced respectively by the first-array antenna elements 2_{11} to 2_{14}, by its associated uplink weight vector, each uplink weight vector corresponding to a different preselected trial uplink beam pattern. The uplink beam patterns have, for example, different beam directions covering a particular sector of the base station. The partial products of the multiplication are summed in the combiners 6_1 to 6_4 to produce output signals corresponding respectively to the trial beam patterns. The beam selector 8 compares the output signals and selects the best trial beam pattern for detecting the uplink signal from the present desired user. Alternatively, instead of selecting just one best beam pattern, the beam selector 8 may perform an interpolation operation to derive a further weight vector corresponding to a beam pattern having a direction between two or more comparably-good different trial beam patterns. The result of this selection/interpolation is output to the receiver circuitry 10, which uses the output signal for the best trial beam pattern directly to perform signal reception on the uplink signals from the desired user.

The beam selector 8 outputs a user DOA signal which, in this embodiment, simply provides the identity of the selected best uplink beam pattern or, if interpolation is used, the identities of the best

uplink beam patterns. This user DOA signal effectively defines an expected DOA of uplink signals from the particular desired user. This user DOA signal is output to the UDR 14 and the optimum weights computation unit 12 in the transmission apparatus.

The UDR 14 stores predetermined types of information about each user. In this embodiment, the UDR stores the DOA, the power level and the bit rate each user is operating at. This information is regularly updated for example, every frame, or every timeslot within a frame, or dynamically at intervals determined by operating parameters of the apparatus.

In the vulnerable users selection unit 16, the user information stored in the UDR 14 is used to determine one or more of the following: the DOA information for the desired user, users nearest to the base station, users who are close to clusters of other users, and users who are close to high bit rate users. Then, using suitable criteria, that information can be used to generate a list of vulnerable users associated with every user. Different examples of criteria which can be used to generate a list of vulnerable users will be described in detail hereinbelow with reference to Figures 4, 5, 6 and 7. It should be noted that the criteria used may be fixed or made dynamic and may vary depending on the particular environment or scenario. For example, in environments where there is a high proportion of high-bit-rate users or clusters of high-bit-rate users, the criteria for determining vulnerable users might advantageously be to minimise the adverse effect on/of these high-bit-rate users / user clusters. On the other hand, in cells whose range is extended, the distance between the users and the base station becomes an important criterion.

Once the list of vulnerable users associated with the desired user has been generated in the vulnerable

users selection unit 16, the DOA of each vulnerable user is output to the optimum weights computation unit 12.

The optimum weights computation unit 12 calculates a set of weights defining a downlink beam pattern which has its main lobe in the direction of the desired user and preferably has nulls in the directions of some or all of the most vulnerable users. It should be noted that however vulnerable the corresponding user, a null should not be placed in the main beam of the beam pattern as this would degrade the downlink beam pattern. It should also be noted that for an array of N elements, it is mathematically possible to form up to N-1 nulls. Therefore, in this embodiment in which there are 4 elements in the second array of antenna elements 2_{21} to 2_{24}, the maximum number of nulls which can be formed at any time is 3.

Once the weights have been calculated by the optimum weights computation unit 12, these are multiplied, in the downlink beamformer 20, with the data to be transmitted to the desired user received from the transmitter circuitry 18. The resulting transmit signals are then transmitted via the second array of antenna elements 2_{21} to 2_{24}.

It will be appreciated that the first and second arrays of antenna elements in the Figure 1 base station do not have to be physically distinct. One physical array of antenna elements could serve, in any of, for example, a time-division-multiplexed, frequency-division-multiplexed or code-division-multiplexed fashion, both for uplink reception and downlink transmission purposes.

Figure 2 is a block diagram illustrating parts of a base station according to a second embodiment of the present invention. In this embodiment, adaptive uplink beamforming is implemented. Components of the Figure 2

apparatus which correspond to components already described with reference to Figure 1 will be denoted by the same reference numerals.

In place of the multiple vector multiplier unit 4, the set of combiners 6_1 to 6_4 and the beam selector 8 used in the receiving apparatus of the first embodiment, receiving apparatus in the second embodiment comprises a vector multiplier 22, a combiner 24, an adaptive algorithm unit 26, and an adder 28. The vector multiplier 22 includes complex-conjugate multipliers equal in number to the antenna elements of the first array. The vector multiplier 22 has four signal inputs, corresponding respectively to the antenna elements 2_{11} to 2_{14}, and a weight vector input coupled to an output of the adaptive algorithm unit 26. The signal outputs of the vector multiplier 22 are coupled to respective inputs of the combiner 24. An output of the combiner 24 is connected both to the receiver circuitry 10 and to a positive input of the adder 28. The adder 28 also has a negative input at which it receives a reference signal. An error signal produced at an output of the adder 28 is coupled to an input of the adaptive algorithm unit 26. The adaptive algorithm unit 26 has further signal inputs connected to the first array of antenna elements 2_{11} to 2_{14}.

In the Figure 2 embodiment the transmission apparatus further comprises a DOA determining unit 30 having a weight vector input connected to the adaptive algorithm unit 26. A user DOA signal produced at an output of the DOA determining unit 30 is coupled to inputs of the UDR 14 and the optimum weights computation unit 12.

Operation of the Figure 2 apparatus will now be described. In use, the vector multiplier 22, the combiner 24, the adder 28 and the adaptive algorithm unit 26 together serve as an adaptive uplink

beamformer. In the vector multiplier 22 receive signals derived from the antenna elements 2_{12} to 2_{14} are multiplied by corresponding weights of a variable weight vector supplied by the adaptive algorithm unit 26. This variable weight vector defines an adaptable uplink beam pattern for use by the receiving apparatus to process the receive signals. The partial products output by the vector multiplier 22 are summed together by the first combiner 24 and the result is output to the receiver circuitry 10 which performs signal detection. The output of the combiner 24 is compared with a reference signal using the adder 28. This reference signal is, for example, generated based on the received uplink signals after detection by the receiver circuitry 10. The resulting error signal produced by the adder 28 is fed back to the adaptive algorithm unit 26 as an indication of how good the current weight vector is. The adaptive algorithm unit 26 uses an adaptive algorithm to update the variable weight vector.

The updated weight vector is also output to the DOA determining unit 30. Assuming the adaptive algorithm used in the adaptive algorithm unit 26 is fairly stable, an estimate of the DOA of the desired user can be derived from the weight vector corresponding to the uplink beam pattern determined for that user. This could be done, for example, by finding the peak of the uplink beam pattern (e.g. by calculating the uplink beamformer gain at different DOAs and identifying the DOA for which the gain is the highest). This DOA estimate is stored at the UDR 14 in an entry therein corresponding to the desired user.

Figure 3 is a flowchart showing a sequence of steps for transmitting a downlink signal to one desired user in an embodiment of the present invention.

In step S1, the last-known DOA of the desired user

is determined using data stored in the UDR in response to reception of a preceding uplink signal from that user.

Then, in step S2, it is determined whether there is a list of vulnerable users (vulnerable list) associated with the transmission to the desired user. Methods for producing such a vulnerable list will be described in detail with reference to Figures 4, 5, 6 and 7. If there is a vulnerable list associated with the transmission, then step S3 is executed. If, on the other hand, the vulnerable list is empty, control moves to step S6.

In step S3 any users in the vulnerable list for whom the provision of a null in the downlink beam pattern for the desired user would degrade that pattern unduly are removed from the vulnerable list. One possible way of doing this is to compare the DOA of each user in the vulnerable list with the DOA of the desired user. If the DOA of a user in the vulnerable list falls within a certain angular range of the DOA of the desired user, then a null corresponding to this vulnerable user would fall within a main beam of the downlink beam pattern. Such a null would degrade the transmission pattern and therefore this user should be removed from the vulnerable list. It will be noted that the required angular separation between the main beam and a null may be determined by the beam width of the main beam which can be calculated as a function of the number of elements and the inter-element spacing. In an embodiment of the present invention this might work out as approximately 10°.

Then, in step S4, it is determined whether there are any users left in the vulnerable list. If there are, control moves to step S5. If not, control moves to step S6.

In step S5, weights are computed (or suitable

weights are selected from amongst a set of predetermined weights) which will generate a downlink beam pattern comprising a main beam in the direction of the desired user and nulls in the directions of up to N-1 vulnerable users (where N is the number of antenna elements). If there are more than N-1 vulnerable users in the vulnerable list, the N-1 most vulnerable users can be selected. To this end, as described later with reference to Figures 4 to 7, the users in the vulnerable list are preferably sorted into descending order of vulnerability in the vulnerable users selection unit 16, and then the first N-1 users in the list are selected.

Any suitable technique or algorithm can be used to compute the appropriate weights based on the DOA information for the desired user and the vulnerable users. Examples of possible techniques can be found in a paper by B. Van Veen and K. Buckley entitled "Beamforming: a versatile approach to spatial filtering" IEEE ASSP Magazine, April 1988, pp. 4 - 24, and also in a book by J. Hudson entitled "Adaptive Array Principles" published by Peter Peregrinus Ltd, London, 1981. When calculating the weights, using one of these techniques, appropriate constraints are used to achieve a main beam directed at the desired user and some of the nulls in the directions of some of the most vulnerable users.

Theoretically, an N element array can generate up to N-1 nulls. However, the locations of the nulls have to be outside the main beam to prevent its distortion. The allowed locations of the nulls are dependent on the array resolution, which in turn is influenced by the number of elements in the antenna array.

As mentioned above, the required weights can alternatively be selected from a set of available weights. In this case it is possible to select, as

appropriate weights, weights which produce a downlink beam pattern whose natural nulls correspond to the DOAs of at least some of the vulnerable users without significantly mis-pointing the main beam.

In step S6, which is executed if the vulnerable list is empty, according to either step S2 or step S4, weights are selected or computed that produce a beam pattern having a main beam directed in the desired user's determined uplink DOA, without reference to other users.

After each of steps S5 and S6, step S7 is executed. In step S7, data is transmitted to the desired user using the weights selected/computed according to step S5 or step S6.

Figures 4, 5, 6 and 7 are flowcharts illustrating how different criteria can be used for the selection of vulnerable users in the selection of vulnerable users unit 16 of Figures 1 and 2. The used criterion (criteria) will depend on the particular application and environment, and may change as the environment changes.

In the examples of Figures 4, 5, 6 and 7, the vulnerable list for a particular desired user is constructed in two stages prior to a downlink signal transmission to that user.

The first stage is to determine whether the downlink signal transmission concerned could cause excessive interference to other users. In this stage, based on certain criteria, a decision is made as to whether there could be some users who are vulnerable to the current transmission. If the decision in the first stage is that the transmission is unlikely to cause adverse effects to other users, then there is no need for any further processing and the vulnerable list = 0 (i.e. is empty). However, if it is decided in the first stage that there could be other vulnerable users,

the second stage is to construct the vulnerable list, that is a list of users that could be adversely affected by the current transmission. Certain criteria, which may be the same or different from those used in the first stage, are used to determine the degree of vulnerability of every user to the transmission to the desired user, and the users considered vulnerable are listed in the vulnerable list in descending order of vulnerability.

Figure 4 is a flowchart illustrating distance-based selection of vulnerable users. This might be suitable for cells with large coverage areas where different mobile users could experience significantly different path losses.

In step S11 it is determined whether the distance from the base station to the desired user's mobile station is greater than a predetermined distance threshold. If it is not, the transmission to that mobile station is unlikely to adversely affect other users, since the transmission will be at a relatively low power, and control moves to step S13 in which the vulnerable list is set to an empty state (vulnerable list = 0) whereupon processing ends.

If the desired user's mobile station's distance from the base station is greater than the distance threshold, however, control moves to S12. In step S12, the vulnerable list is formed as a list of all other users sorted in ascending order of their distance to the base station.

Then, in step S14, any users in the vulnerable list which belong to a cluster (i.e. are located near one another) are identified. This could be done, for example, by comparing the distances and DOAs of the users in the vulnerable list. Entries in the list for those users which belong to a cluster are replaced by a "cluster" entry in the list that has its DOA set equal

to the mean DOA of cluster concerned. This makes it possible to form nulls in the respective DOAs of the clusters.

Figure 5 is a flowchart illustrating bit-rate based selection of vulnerable users. This might be suitable for small cells that typically serve a significant number of high data/bit rate users.

In step S21, it is determined whether the desired user is a high data rate user. The data rate a given user is operating at is readily available to the base station, so this can be done simply by setting a threshold data rate above which a user is considered to be a high data rate user.

If the user is not a high data rate user then control moves to step S23. In step S23 the vulnerable list is set to the empty state and processing ends.

If, however, the desired user is a high data rate user according to step S21 control moves to step S22. In step S22 it is determined whether there are any clusters of users. If there are not any clusters of users then control moves to step S23 where the vulnerable list is also set to the empty state.

In this embodiment only if there is a high bit rate user and there is at least one cluster of users, who may be but are not necessarily high-bit-rate users, then, in step S24 entries are made in the vulnerable list for the clusters in descending order of cluster sizes. As before, the entry for each cluster has its DOA set to the mean DOA of the users in the cluster concerned.

Figure 6 is a flowchart illustrating a combined bit rate and distance based selection of vulnerable users. This might be suitable for large cells with a large number of high bit rate users.

In step S31 it is determined whether the desired user is a high data rate user. If so, then control

moves to step S34. If not, then control moves to step S32.

In step S32 it is determined whether the distance from the base station to the desired user mobile is greater than a predetermined distance threshold. If it is, then, as in S31, control moves to step S34. If it is not, control moves to step S33.

Thus, in this embodiment it is decided to form a vulnerable list when the desired user is a high data rate user or further than the distance threshold from the base station.

In step S33, which is executed when the desired user is neither a high data rate user nor further from the base station than the distance threshold, the vulnerable list is set to the empty state and processing ends.

In step S34, in one implementation, the vulnerable list is set equal to a list of all other users sorted in ascending order of their distance from the base station. In another implementation, the vulnerable list is set equal to a list of all other users in descending order of their data rates. If desired, the users in the vulnerable list may be sorted according to a combination of the distance and data rate criteria.

Then, in step S35, entries for users in the vulnerable list that belong to a cluster are replaced by a cluster entry whose DOA is set equal to the mean DOA of the users in the cluster concerned.

Figure 7 is a flowchart illustrating a modification of the process of selecting vulnerable users according to Figure 6. Steps in the Figure 7 flowchart which correspond to steps already described with reference to Figure 6 will be denoted by the same reference numerals.

This modified selection process applies a weighting process to the desired user's data rate and

distance from the base station and combines the results of the weightings to form a measure of the desired user's potential adverse effect on other users. Weightings α and β for a desired user could be calculated as follows:

$$\alpha = \frac{\text{Desired User's Data Rate}}{\text{Data Rate Threshold}} \tag{1}$$

$$\beta = \frac{\text{Desired User's Distance to Base Station}}{\text{Distance Threshold}} \tag{2}$$

In step S41, the weightings α and β are summed and the measure $\alpha+\beta$ is used to determine whether it is necessary to protect any vulnerable users from a downlink transmission to the desired user. The value of a threshold for the measure $\alpha+\beta$ could be set appropriately at the base station. According to step S41, if the measure $\alpha+\beta$ is greater than the threshold value then control moves to steps S34 and S35, which were described hereinbefore with reference to Figure 6. If the measure $\alpha+\beta$ is less than the threshold value then control moves to step S33, which is also described hereinbefore with reference to Figure 6.

CLAIMS:

1. A transmission method, for use in a base station of a mobile communications network, including the steps of:

identifying, for a particular mobile user of the network, one or more other mobile users that are to be treated as vulnerable users potentially adversely affected by a downlink signal transmission from the base station to the particular mobile user;

determining a downlink beam pattern including a main beam having a direction matching a direction of the particular mobile user and also including a null having a direction matching a direction of at least one of the said vulnerable users; and

transmitting such a downlink signal to the said particular mobile user using the determined beam pattern.

2. A method as claimed in claim 1, wherein the said direction of the said particular mobile user and of the or each said vulnerable user is determined by processing an uplink signal received at the base station from the user concerned.

3. A method as claimed in claim 1 or 2, wherein the said direction of the said particular mobile user and of the or each said vulnerable user is derived from an uplink beam pattern employed by the base station to process a received uplink signal from the user concerned.

4. A method as claimed in claim 3, wherein

the uplink beam pattern is adapted in use by the said base station; and

an estimate of the direction of each said mobile user is derived from an adjustable weight vector corresponding to the uplink beam pattern determined for that user.

5. A method as claimed in any preceding claim, wherein, in the pattern determining step, any identified vulnerable user whose direction would require the said downlink beam pattern to include such a null within, or near to, the said main beam is ignored.

6. A method as claimed in any preceding claim, wherein the said downlink beam pattern is calculated based on the respective directions of the said particular mobile user and the or each said vulnerable user.

7. A method as claimed in any one of claims 1 to 5, wherein the determined downlink beam pattern is a best-matching downlink beam pattern selected from amongst a plurality of predetermined candidate downlink beam patterns.

8. A method as claimed in any preceding claim, further including an interference judging step of judging, for the said particular mobile user, whether, based on one or more predetermined criteria, the said downlink signal transmission to that user is likely to cause significant interference to other mobile users of the network and, if not, of omitting the said step of identifying vulnerable users and of determining the said downlink beam pattern for the particular mobile user independently of the effect of that transmission on other mobile users of the network.

9. A method as claimed in claim 8, wherein the said one or more predetermined criteria used in the interference judging step relate exclusively to the particular mobile user.

10. A method as claimed in claim 8 or 9, wherein the said predetermined criteria used in the interference judging step include one or more of the following:

a measure of the distance of the said particular mobile user from the base station; and a bit rate of the said downlink signal transmission to the said particular mobile user.

11. A method as claimed in any one of claims 8 to 10, wherein in the said interference judging step it is judged that significant interference to other users is likely when a measure of the distance of the said particular mobile user from the base station exceeds a predetermined threshold value.

12. A method as claimed in any one of claims 8 to 11, wherein in the interference judging step it is judged that significant interference to other users is likely when a bit rate of the said particular mobile user exceeds a predetermined threshold value.

13. A method as claimed in any preceding claim, wherein in the step of identifying vulnerable users it is determined whether a mobile user other than the said particular mobile user is to be treated as a vulnerable user in dependence upon one or more of the following criteria:

the direction of that other mobile user, a measure of the distance of that other mobile user from the base station; a bit rate of that other mobile user; a bit rate of that other mobile user; and a proximity of that other mobile user to further mobile users of the network.

14. A method as claimed in claim 13, wherein candidate mobile users other than the said particular mobile user are ranked in order of vulnerability according to the said criteria used in the identifying vulnerable users step and, when the number of other users exceeds the number N_{max} of nulls/low side lobes that it is possible to form in the said downlink beam pattern, the N_{max} most vulnerable candidate users in the said order are selected as vulnerable users for

determining the downlink beam pattern.

15. A method as claimed in any preceding claim, wherein in the identifying vulnerable users step it is determined whether there are any clusters of other users and, if so, the clusters are ranked according to the numbers of users therein.

16. A method as claimed in any preceding claim, wherein vulnerable users that form a cluster are processed collectively as a vulnerable cluster and the downlink beam pattern determined for the said particular mobile user is such as to include such a null having a direction matching a direction of the said vulnerable cluster.

17. A method as claimed in claim 16, wherein the direction of the said vulnerable cluster is determined based on an average of the respective directions of the individual vulnerable users making up the cluster concerned.

18. A method as claimed in claim 10 or 13, wherein the said distance measure for a mobile user is, or is derived from, a transmission power determined by the base station for transmitting a downlink signal to the user concerned.

19. A method as claimed in claim 10 or 13, wherein the said distance measure for a mobile user is, or is derived from, a code time offset of an uplink signal received by the base station from the mobile user concerned.

20. A method as claimed in claim 10 or 13, wherein the said distance measure for a mobile user and/or the said direction of a mobile user is derived from information obtained using a satellite-based global positioning system.

21. A method as claimed in claim 10 or 13, wherein the said distance measure for a mobile user and/or the direction of a mobile user is derived from information obtained using triangulation techniques involving at least three base stations of the said network.

22. Transmission apparatus, for use in a base station of a mobile communications network, comprising:

identification means operable to identify, for a particular mobile user of the network, one or more other mobile users that are to be treated as vulnerable users potentially adversely affected by a downlink signal transmission from the base station to the particular mobile user;

determining means operable to determine a downlink beam pattern including a main beam having a direction matching a direction of the particular mobile user and also including a null having a direction matching a direction of at least one of the said vulnerable users; and

transmission means operable to transmit such a downlink signal to the said particular mobile user using the determined beam pattern.

23. Apparatus as claimed in claim 22, further including:

user data register means operable to store, for each of a plurality of mobile users of the said network, one or more predetermined items of information about the user concerned for use by the identification means to identify vulnerable users and/or by the determining means to determine the downlink beam pattern.

24. Apparatus as claimed in claim 23, wherein the stored items of information about each user include one or more of the following types of information: the direction of the mobile user; a measure of the distance of the mobile user from the base station; a bit rate of the mobile user; a position of the mobile user; and cluster information as to proximity of the mobile user to other mobile users of the network.

25. A base station for use in a mobile communications network, including transmission apparatus as claimed in any one of claims 22 or 24.

26. An angle-of-arrival calculation method, for use in receiving apparatus that includes an antenna array having a plurality of antenna elements for sampling, at different respective locations in space, a wanted signal transmitted to the apparatus and that also includes an adaptive beamformer operable to process a set of receive signals, derived respectively from the antenna elements of the array, in accordance with a beam pattern determined by an adjustable weight vector, the weight vector being adjusted in use of the apparatus in response to changes in an angle-of-arrival of the wanted signal at the antenna array, which method includes the steps of:

processing the said adjustable weight vector to determine an angle-of-arrival of the wanted signal at which the response of the adaptive beamformer has a peak; and

outputting a measure of angle-of-arrival of the said wanted signal based on the determined angle of peak beamformer response.

27. A method as claimed in claim 26, wherein the said processing step comprises:

determining the uplink beam pattern corresponding to the current value of the said adjustable weight vector;

calculating the uplink beamformer gain at a plurality of different possible angles-of-arrival according to the said uplink beam pattern; and

selecting the angle-of-arrival for which the uplink beamformer gain is the greatest.

28. A transmission method substantially as hereinbefore described with reference to the accompanying drawings.

29. Transmission apparatus substantially as hereinbefore described with reference to the accompanying drawings.

30. A base station substantially as hereinbefore described with reference to the accompanying drawings.

31. An angle-of-arrival calculation method substantially as hereinbefore described with reference to the accompanying drawings.

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Application No: GB 9908839.5
Claims searched: 1 to 25

Examiner: M J Billing
Date of search: 16 September 1999

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.Q): H1Q QFA, QFC, QFF, QFH; H4L LDLX, LDSG, LDSL, LECX, LFNX.

Int Cl (Ed.6): H01Q 1/24, 3/26, 3/30, 3/34, 3/36, 3/38, 3/40; H04Q 7/30, 7/36, 7/38

Other: ONLINE - EPODOC, WPI.

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	GB2328800A	(MOTOROLA) - Figs.2,3; page 4 line 1 to page 5 line 11	1,2,6,13, 22 at least
X	GB2318947A	(MOTOROLA) - page 12 lines 9-20, page 13 lines 19-26, page 14 line 20 to page 15 line 28	1,2,6,13, 22 at least
X	GB2316807A	(MATSUSHITA) - Figs.52,53; Abstract, page 18 lines 8-21, page 94 line 16 to page 97 line 7	1,2,6,13, 22 at least
X	GB2307142A	(MOTOROLA) - page 5 lines 3-20, page 6 lines 8-18	1,2,13,21, 22 at least
X	EP0841827A2	(LUCENT) - page 6 lines 8-21, page 11 line 37 to page 18 line 22	1,2,6,13, 22 at least
X,E	WO99/22423A1	(ERICSSON) - Fig.3; page 5 lines 5-8, page 7 lines 9-27, page 9 lines 17-21	1,2,6,13, 22 at least
X	WO98/16077A2	(TERATECH) - page 13 lines 20-23, page 17 line 17 to page 18 line 7	1,2,6,13, 20,22 at least

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

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INVESTOR IN PEOPLE

Application No: GB 9908839.5
Claims searched: 1 to 25
Examiner: M J Billing
Date of search: 16 September 1999

Category	Identity of document and relevant passage		Relevant to claims
X	US5260968	(GARDNER) - column 6 lines 17-26, column 13 lines 3-44	1,2,6,13, 22 at least

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		